Holographic tachyon model of dark energy

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Abstract

In this paper we consider a correspondence between the holographic dark energy density and tachyon energy density in FRW universe. Then we reconstruct the potential and the dynamics of the tachyon field which describe tachyon cosmology.

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1 Introduction

Nowadays it is strongly believed that the universe is experiencing an accelerated expansion. Recent observations from type Ia supernovae [1] in associated with Large Scale Structure [2] and Cosmic Microwave Background anisotropies [3] have provided main evidence for this cosmic acceleration. In order to explain why the cosmic acceleration happens, many theories have been proposed. Although theories of trying to modify Einstein equations constitute a big part of these attempts, the mainstream explanation for this problem, however, is known as theories of dark energy. It is the most accepted idea that a mysterious dominant component, dark energy, with negative pressure, leads to this cosmic acceleration, though its nature and cosmological origin still remain enigmatic at present.

The most obvious theoretical candidate of dark energy is the cosmological constant λ (or vacuum energy) [4, 5] which has the equation of state $w = -1$. An alternative proposal for dark energy is the dynamical dark energy scenario. So far, a large class of scalar-field dark energy models have been studied, including quintessence [6], K-essence [7], tachyon [8], phantom [9], ghost condensate [10, 11] and quintom [12], interacting dark energy models [13], braneworld models [14], and Chaplygin gas models [15], etc.

Currently, an interesting attempt for probing the nature of dark energy within the framework of quantum gravity is the so-called "holographic dark energy" proposal [16, 17]. It was shown by 'tHooft and Susskind [18] that effective local quantum field theories greatly overcount degrees of freedom because the entropy scales extensively for an effective quantum field theory in a box of size L with UV cut-off Λ. As pointed out by [19], attempting to solve this problem, Cohen *et al* showed [20] that in quantum field theory, short distance cut-off Λ is related to long distance cut-off L due to the limit set by forming a black hole. In other words the total energy of the system with size L should not exceed the mass of the same size black hole, i.e. $L^3 \rho_\Lambda \leq L M_p^2$ where ρ_Λ is the quantum zero-point energy density caused by UV cut-off Λ and M_P denotes the Planck mass ($M_p^2 = 1/8\pi G$). The largest L is required to saturate this inequality. Then its holographic energy density is given by $\rho_\Lambda = 3c^2 M_p^2 / 8\pi L^2$ in which c is a free dimensionless parameter and coefficient 3 is for convenience. As an application of the holographic principle in cosmology, it was studied by [21] that the consequence of excluding those degrees of freedom of the system which will never be observed by the effective field theory gives rise to IR cut-off L at the future event horizon. Thus in a universe dominated by DE, the future event horizon will tend to a constant of the order H_0^{-1}, i.e. the present Hubble radius. On the basis of the cosmological state of the holographic principle, proposed by Fischler and Susskind [22], a holographic model of dark Energy (HDE) has been proposed and studied widely in the literature [17, 23]. In the model proposed by [17], it is discussed that considering the particle horizon, as the IR cut-off, the HDE density reads

$$\rho_\Lambda \propto a^{-2(1+\frac{1}{c})}, \tag{1}$$

that implies $w > -1/3$ which does not lead to an accelerated universe. Also it is shown in [24] that for the case of closed universe, it violates the holographic bound.

The problem of taking apparent horizon (Hubble horizon) - the outermost surface defined by the null rays which instantaneously are not expanding, $R_A = 1/H$ - as the IR cut-off in the flat universe was discussed by Hsu [25]. According to Hsu's argument, employing the Friedmann equation $\rho = 3M_P^2 H^2$ where ρ is the total energy density and taking $L = H^{-1}$

we will find $\rho_m = 3(1-c^2)M_P^2 H^2$. Thus either ρ_m or ρ_Λ behave as H^2. So the DE results as pressureless, since ρ_Λ scales like matter energy density ρ_m with the scale factor a as a^{-3}. Also, taking the apparent horizon as the IR cut-off may result in a constant parameter of state w, which is in contradiction with recent observations implying variable w [26]. On the other hand taking the event horizon, as the IR cut-off, gives results compatible with observations for a flat universe.

In this paper, we consider the issue of the tachyon as a source of the dark energy. The tachyon is an unstable field which has become important in string theory through its role in the Dirac-Born-Infeld (DBI) action which is used to describe the D-brane action [27, 28]. It has been noticed that the cosmological model based on effective lagrangian of tachyon matter

$$L = -V(T)\sqrt{1 - T_{,\mu}T^{,\mu}} \tag{2}$$

with the potential $V(T) = \sqrt{A}$ exactly coincides with the Chaplygin gas model [29, 30]. In the other hand, it has been pointed out that the Chaplygin gas model can be described by a quintessence field with well-connected potential [15].

In the present paper, we suggest a correspondence between the holographic dark energy scenario and tachyon dark energy model. We show this holographic description of tachyon dark energy in FRW universe and reconstruct the potential and the dynamics of the scalar field which describe the tachyon cosmology. The present paper extend previous our investigations [31] in which similar studies were done for a Chaplygin gas model.

2   Tachyon field as holographic dark energy in flat universe

Here we consider a four-dimensional, spatially -flat Friedmann-Robertson-Walker universe, the Friedmann equations are as

$$H^2 = \frac{8\pi G}{3}\rho, \tag{3}$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G(\rho + 3P)}{3} \tag{4}$$

where $\rho = \rho_{NR} + \rho_R + \rho_T$ is the energy density for, respectively, non-relativistic, relativistic and tachyon matter, and P is the corresponding pressure. We shall restrict ourselves to consider a description of the current cosmic situation where it is assumed that the tachyon component largely dominates and therefore we shall disregard in what follows the non-relativistic and relativistic components of the matter density and pressure. In this case the first Friedmann equation is as

$$H^2 = \frac{8\pi G}{3}\rho_T, \tag{5}$$

The energy density and pressure for the tachyon field are as following [28]

$$\rho_T = \frac{V(T)}{\sqrt{1 - \dot{T}^2}}, \qquad P_T = -V(T)\sqrt{1 - \dot{T}^2} \tag{6}$$

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where $V(T)$ is the tachyon potential energy. The barotropic index for the tachyon is

$$w_T = \dot{T}^2 - 1 \tag{7}$$

Now we suggest a correspondence between the holographic dark energy scenario and the tachyon dark energy model. In flat universe, our choice for holographic dark energy density is

$$\rho_\Lambda = 3c^2 M_p^2 R_h^{-2}. \tag{8}$$

where $M_p^2 = \frac{1}{8\pi G}$ and

$$R_h = a \int_t^\infty \frac{dt}{a} = a \int_a^\infty \frac{da}{Ha^2} \tag{9}$$

So,

$$w_\Lambda = \frac{-1}{3} - \frac{2}{3c} \tag{10}$$

If we establish the correspondence between the holographic dark energy and tachyon energy density, then using Eqs.(6,8) we have

$$\rho_\Lambda = 3c^2 M_p^2 R_h^{-2} = \frac{V(T)}{\sqrt{1 - \dot{T}^2}}. \tag{11}$$

Also using Eqs.(7, 31), one can write

$$w_\Lambda = \frac{-1}{3} - \frac{2}{3c} = \dot{T}^2 - 1 \tag{12}$$

then

$$\dot{T} = \sqrt{\frac{2}{3}(1 - \frac{1}{c})} \tag{13}$$

We can easily obtain the evolutionary form of the tachyon field

$$T = T_0 + \sqrt{\frac{2}{3}(1 - \frac{1}{c})}t \tag{14}$$

Now using Eq.(11) we can obtain the tachyon potential energy as

$$V(T) = 3c^2 M_p^2 R_h^{-2} \sqrt{\frac{1}{3}(1 + \frac{2}{c})} \tag{15}$$

If we take $c = 1$, then the behaviour of tachyon field is similar to the cosmological constant, $\dot{T} = 0$, $w_\Lambda = -1$, in this case

$$T = T_0 = constant, \qquad V(T) = 3c^2 M_p^2 R_h^{-2} \tag{16}$$

The choice $c < 1$ will leads to tachyon dark energy behaving as phantom. Such a regime can be obtained by simply Wick rotating the tachyon field so that $T \to iT$.

3 Tachyon field as holographic dark energy in non-flat universe

In this section we extend the calculations of the previous section to the non-flat universe. The first Friedmann equation is given by

$$H^2 + \frac{k}{a^2} = \frac{1}{3M_p^2}\Big[\rho_\Lambda + \rho_m\Big]. \tag{17}$$

where k denotes the curvature of space k=0,1,-1 for flat, closed and open universe respectively. Define as usual

$$\Omega_m = \frac{\rho_m}{\rho_{cr}} = \frac{\rho_m}{3M_p^2 H^2}, \qquad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}} = \frac{\rho_\Lambda}{3M_p^2 H^2}, \qquad \Omega_k = \frac{k}{a^2 H^2} \tag{18}$$

In non-flat universe, our choice for holographic dark energy density is

$$\rho_\Lambda = 3c^2 M_p^2 L^{-2}. \tag{19}$$

L is defined as the following form[32]:

$$L = ar(t), \tag{20}$$

here, a, is scale factor and $r(t)$ is relevant to the future event horizon of the universe. Given the fact that

$$\int_0^{r_1} \frac{dr}{\sqrt{1-kr^2}} = \frac{1}{\sqrt{|k|}}\text{sinn}^{-1}(\sqrt{|k|}\,r_1)$$

$$= \begin{cases} \sin^{-1}(\sqrt{|k|}\,r_1)/\sqrt{|k|}, & k=1, \\ r_1, & k=0, \\ \sinh^{-1}(\sqrt{|k|}\,r_1)/\sqrt{|k|}, & k=-1, \end{cases} \tag{21}$$

one can easily derive

$$L = \frac{a(t)\text{sinn}[\sqrt{|k|}\,R_h(t)/a(t)]}{\sqrt{|k|}}, \tag{22}$$

where R_h is the future event horizon given by (9). By considering the definition of holographic energy density ρ_Λ, one can find [33, 34]:

$$w_\Lambda = -[\frac{1}{3} + \frac{2\sqrt{\Omega_\Lambda}}{3c}\frac{1}{\sqrt{|k|}}\text{cosn}(\sqrt{|k|}\,R_h/a)]. \tag{23}$$

where

$$\frac{1}{\sqrt{|k|}}\text{cosn}(\sqrt{|k|}x) = \begin{cases} \cos(x), & k=1, \\ 1, & k=0, \\ \cosh(x), & k=-1. \end{cases} \tag{24}$$

If again we establish the correspondence between the holographic dark energy and tachyon energy density, then using Eqs.(6,19) we have

$$\rho_\Lambda = 3c^2 M_p^2 L^{-2} = \frac{V(T)}{\sqrt{1 - \dot{T}^2}}. \tag{25}$$

Also using Eqs.(7, 23), one can write

$$w_\Lambda = -[\frac{1}{3} + \frac{2\sqrt{\Omega_\Lambda}}{3c} \frac{1}{\sqrt{|k|}} \cosn(\sqrt{|k|}\, R_h/a)] = \dot{T}^2 - 1 \tag{26}$$

then

$$\dot{T} = \sqrt{\frac{2}{3}[1 - \frac{\sqrt{\Omega_\Lambda}}{c} \frac{1}{\sqrt{|k|}} \cosn(\sqrt{|k|}\, R_h/a)]} \tag{27}$$

Now using Eq.(25) we can obtain the tachyon potential energy as

$$V(T) = 3c^2 M_p^2 L^{-2} \sqrt{\frac{1}{3}[1 + \frac{2\sqrt{\Omega_\Lambda}}{c} \frac{1}{\sqrt{|k|}} \cosn(\sqrt{|k|}\, R_h/a)]} \tag{28}$$

Differenating Eq.(17) with respect to the cosmic time t, one find

$$\dot{H} = \frac{\dot{\rho}}{6HM_p^2} + \frac{k}{a^2} \tag{29}$$

where $\rho = \rho_m + \rho_\Lambda$ is the total energy density. Now we write continuity equation for dark energy and cold dark matter as

$$\dot{\rho} = -3H(1 + w)\rho \tag{30}$$

where

$$w = \frac{w_\Lambda \rho_\Lambda}{\rho} = \frac{\Omega_\Lambda w_\Lambda}{1 + \frac{k}{a^2 H^2}} \tag{31}$$

Substitute $\dot{\rho}$ into Eq.(29), we obtain

$$w = \frac{2/3(\frac{k}{a^2} - \dot{H})}{H^2 + \frac{k}{a^2}} - 1 \tag{32}$$

Using Eqs.(31, 32), one can rewrite the holographic energy equation of state as

$$w_\Lambda = \frac{-1}{3\Omega_\Lambda H^2}(2\dot{H} + 3H^2 + \frac{k}{a^2}) \tag{33}$$

Therefore one can rewrite Eqs.(27,28) respectively as

$$\dot{T}^2 = 1 - \frac{1}{3\Omega_\Lambda H^2}(2\dot{H} + 3H^2 + \frac{k}{a^2}) \tag{34}$$

$$V(T) = \frac{3c^2 M_p^2}{HL^2} \sqrt{\frac{2\dot{H} + 3H^2 + \frac{k}{a^2}}{3\Omega_\Lambda}} \tag{35}$$

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Using definitions $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{cr}}$ and $\rho_{cr} = 3M_p^2 H^2$, we get

$$HL = \frac{c}{\sqrt{\Omega_\Lambda}} \tag{36}$$

then

$$V(T) = HM_p^2 \sqrt{3\Omega_\Lambda (2\dot{H} + 3H^2 + \frac{k}{a^2})} \tag{37}$$

In similar to the [35, 36, 37], we can define $\dot{T}^2$ and $V(T)$ in terms of single function $f(T)$ as

$$-1 = 1 - \frac{1}{3\Omega_\Lambda f^2(T)}[2f'(T) + 3f^2(T) + \frac{k}{a^2}] \tag{38}$$

$$V(T) = f(T)M_p^2 \sqrt{3\Omega_\Lambda [2f'(T) + 3f^2(T) + \frac{k}{a^2}]} \tag{39}$$

Hence, the following solution are obtained

$$T = it, \qquad H = f(it) \tag{40}$$

From Eq.(38) we get

$$\frac{k}{a^2} = 3f^2(T)(2\Omega_\Lambda - 1) - 2f'(T) \tag{41}$$

Substitute the above $\frac{k}{a^2}$ into Eq.(39), we obtain the tachyon potential as

$$V(T) = 3\sqrt{2}M_p^2\Omega_\Lambda f^2(T) \tag{42}$$

One can check that the solution (40) satisfies the following tachyon field equation

$$\frac{\ddot{T}}{1 - \dot{T}^2} + 3H\dot{T} + \frac{V'}{V} = 0 \tag{43}$$

Therefore by the above condition and using Eq(42), $f(T)$ in our model must satisfy following relation

$$3if(T) + \frac{2f'(T)}{f(T)} = 0 \tag{44}$$

Elementary algebra now gives the $f(T)$ to be of the form

$$f(T) = \frac{2}{3iT} \tag{45}$$

In this case, we can determine the potential to be

$$V(T) = \frac{-4\sqrt{2}}{3}M_p^2\Omega_\Lambda \frac{1}{T^2} \tag{46}$$

For the tachyon self-interaction, there are a number of models which one can consider, some being motivated by non-perturbative string theory and others purely by phenomenology. The authors of [38] have studied a wide renge of potentials, they have shown that in the presence of a tachyon field T with potential $V(T)$ and a barotropic perfect fluids, the cosmological dynamics depends on the asymptotic behavior of the quantity $\lambda = \frac{-M_p V'}{V^{3/2}}$.

7

If λ is a constant, which corresponds to an inverse square potential $V(T) \propto T^{-2}$, there exists one stable critical point that gives an acceleration of the universe at late times. [1] With this result we can claim that only the potentials which have the above form are consistent with the holographic approach of tachyon dark energy model. The property of the holographic dark energy is strongly depend on the parameter c. From Eqs.(33), (37) we have

$$V(T) = H M_p^2 \sqrt{-9\Omega_\Lambda^2 H^2 w_\Lambda} = 3H^2 M_p^2 \Omega_\Lambda \sqrt{-w_\Lambda} \tag{50}$$

Substitute w_Λ into the above equation

$$V(T) = 3H^2 M_p^2 \Omega_\Lambda \sqrt{[\frac{1}{3} + \frac{2\sqrt{\Omega_\Lambda}}{3c} \frac{1}{\sqrt{|k|}} \mathrm{cosn}(\sqrt{|k|}\, R_h/a)]} \tag{51}$$

In the flat case we have

$$V(T) = 3H^2 M_p^2 \Omega_\Lambda \sqrt{\frac{1}{3}(1 + \frac{2\sqrt{\Omega_\Lambda}}{c})} \tag{52}$$

which is exactly Eq.(15) in [39]. [2] The holographic dark energy model has been tested and constrained by various astronomical observations, in both flat and non-flat cases. These observational data include type Ia supernovae, cosmic microwave background, baryon acoustic oscillation, and the X-ray gas mass fraction of galaxy clusters. According to the analysis of the observational data for the holographic dark energy model, we find that generally $c < 1$, and the holographic dark energy thus behaves like a quintom-type dark energy. When including the spatial curvature contribution, the fitting result shows that the closed universe is marginally favored. For the closed universe the equation of state is given by [3]

$$w_\Lambda = \frac{-1}{3}(1 + \frac{2\sqrt{\Omega_\Lambda}}{c}\cos x) \tag{53}$$

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[1]Ω_Λ is not constant, the differential equation for Ω_Λ is

$$\frac{d\Omega_\Lambda}{dx} = \frac{\dot{\Omega}_\Lambda}{H} = 3\Omega_\Lambda(1 + \Omega_k - \Omega_\Lambda)[\frac{1}{3} + \frac{2\sqrt{\Omega_\Lambda}}{3c}\frac{1}{\sqrt{|k|}}\mathrm{cosn}(\sqrt{|k|}\,R_h/a)] \tag{47}$$

where $x = \ln a$. The above equation describes the behavior of the holographic dark energy completely, in the spatially flat case, i.e, $k = 0$:

$$\frac{d\Omega_\Lambda}{dx} = \frac{\dot{\Omega}_\Lambda}{H} = \Omega_\Lambda(1 + \Omega_k - \Omega_\Lambda)[1 + \frac{2\sqrt{\Omega_\Lambda}}{c}] \tag{48}$$

it can be solved exactly for arbitrary c, the solution for $c = 1$ [17] is as following

$$\ln\Omega_\Lambda - \frac{1}{3}(1 - \sqrt{\Omega_\Lambda}) + (1 + 2\sqrt{\Omega_\Lambda}) - \frac{8}{3}(1 + \sqrt{\Omega_\Lambda}) = \ln a + x_0 \tag{49}$$

where x_0 fixed by L.H.S. of (49) with Ω_Λ and a replaced with present time values. From Eq.(40) one can see that Ω_Λ depend to T, therefore, the potential (46) does not only vary as T^{-2}, but at late time Ω_Λ increases to 1. Then it is interesting that in our model, at late time where $\Omega_\Lambda = 1$, we obtain $V(T) \propto T^{-2}$, similar to the result of [38]. In fact only in this case potential is as $V(T)$. The additional dependence through Ω_Λ makes it dependent not only on the tachyon field but through H^2, on the matter component as well.

[2]This reference appeared on the arXiv by the number arXiv:0706.1185 [astro-ph] after my submission to the arXxiv with number arXiv:0705.3517 [hep-th].

[3]Flat case is discussed in [39]

then $\frac{-1}{3}(1 + \frac{2}{c}) \leq w_\Lambda \leq \frac{-1}{3}(1 - \frac{2}{c})$, when $0 \leq \Omega_\Lambda \leq 1$. Similar to the flat case, when $c < 1$, the equation of state cross $w_\Lambda = -1$ (from $w_\Lambda > -1$ evolves to $w_\Lambda < -1$). When $c > 2$, w_Λ evolve in the region $-1 < w_\Lambda < 0$. Since the equation of state of tachyon field also evolves in this region, then one can say, in the closed universe case we can consider a correspondence between the holographic dark energy density and tachyon energy density if $c > 2$. If we take $c = 1$, and taking $\Omega_\Lambda = 0.73$ for the present time, the lower bound of w_Λ is -0.9. Therefore it is impossible to have w_Λ crossing -1. This implies that one can not generate phantom-like equation of state from an holographic dark energy model with $c = 1$ in non-flat universe. In the other hand as we have shown previously with the choice of $c \leq 0.84$, the interacting holographic dark energy can be described by a phantom scalar field [37]. Therefore the parameter c plays a crucial role in the model.

4   Conclusions

Based on cosmological state of holographic principle, proposed by Fischler and Susskind [22], the Holographic model of Dark Energy (HDE) has been proposed and studied widely in the literature [17, 23]. In [40] using the type Ia supernova data, the model of HDE is constrained once when c is unity and another time when c is taken as free parameter. It is concluded that the HDE is consistent with recent observations, but future observations are needed to constrain this model more precisely.

Within the different candidates to play the role of the dark energy, tachyon, has emerged as a possible source of dark energy for a particular class of potentials [41].

In this paper we have associated the holographic dark energy in FRW universe with a tachyon field which describe the tachyon cosmology. We have shown that the holographic dark energy can be described by the tachyon field in a certain way. Then a correspondence between the holographic dark energy and tachyon model of dark energy has been established, and the potential of the holographic tachyon field and the dynamics of the field have been reconstructed. For the holographic tachyon model constructed in the present paper, the tachyon potential can be determined by Eq.(46). We saw that the parameter c plays a crucial role in the model: $c \geq 1$ makes the holographic dark energy behave as quintessence-type dark energy with $w_\Lambda \geq -1$, and $c < 1$ makes the holographic dark energy behave as quintom-type dark energy with w_Λ crossing -1 during the evolution history. Hence, we see, the determining of the value of c is a key point to the feature of the holographic dark energy and the ultimate fate of the universe as well. However, in the recent fit studies, different groups gave different values to c. A direct fit of the present available SNe Ia data with this holographic model indicates that the best fit result is $c = 0.21$ [40]. Recently, by calculating the average equation of state of the dark energy and the angular scale of the acoustic oscillation from the BOOMERANG and WMAP data on the CMB to constrain the holographic dark energy model, the authors show that the reasonable result is $c \sim 0.7$ [42]. In the other hand, in the study of the constraints on the dark energy from the holographic connection to the small l CMB suppression, an opposite result is derived, i.e. it implies the best fit result is $c = 2.1$ [43].

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